Measurement and Analysis of High-Frequency Scattering Statistics and Sound Speed Dispersion

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LONG-TERM GOALS

The long-term goal of the present high-frequency scattering statistics work is to link the high-frequency reverberation envelope distribution to measurable seafloor geoacoustic properties in conjunction with sonar system parameters (such as frequency and resolution cell size), providing the foundation necessary for solving several problems related to the detection of targets in non-Rayleigh clutter. A direct link between system and environmental parameters via scattering models to the statistical distribution of reverberation will allow: performance prediction for different systems based on seafloor properties, extrapolation of performance to other system/bandwidths, and optimization of system parameters such as frequency/bandwidth to the local environment.

The long-term goal of the sound speed measurement initiative is to contribute to the assessment of different physical models for porous media to be assessed and evaluated based on the unique sound speed dispersions that they predict. This knowledge concerning the most suitable physical model for the seabed, and its limitations, can be used to improve the performance of mine hunting sonar systems.

OBJECTIVES

The objectives of the high-frequency scattering statistics project are to (1) collect and use experimental data determine the primary environmental properties that can influence the frequency and range dependence of amplitude distributions obtained with high-frequency acoustic systems (e.g. synthetic aperture sonar) in shallow water; (2) develop and use high-frequency scattering models together with collected ground truth to determine the scattering properties of patchy seafloors; (3) test current models or develop models where none exist which link environmental parameters and system characteristics to predict scattered amplitude statistics as a function of frequency and range for complex environments.

The objectives of the sound speed dispersion work are to participate in the component of the SAX04 experiments dealing with the speed of sound in a surficial layer of sand. In particular: 1) experimental concepts will be developed and implemented to measure the anticipated sound speed dispersion from approximately 500 to 10,000 Hz, 2), vector sensor array data will be collected and analyzed as part of the SAX04 sea-trial, and 3) numerical model simulations will be developed and compared with experimental data.

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APPROACH

Work has been conducted recently at the Applied Research Laboratory – Penn State University (ARL-PSU) to model high-frequency scattered amplitude statistics from seafloors with discrete scatterers as well as those with patches of differing scattering properties. What is lacking are experimental studies designed to link these models of amplitude statistics to scattering models in order to improve predictive capabilities for high-frequency acoustic systems operating in shallow water areas that have spatially heterogeneous seafloors. High-frequency seafloor scattering data will be analyzed from several high-frequency experiments which took place over the last three years which were part of a Joint Research Project (JRP) between the NATO Undersea Research Centre (NURC) and ARL-PSU and the SAX04 experiment off of Ft. Walton Beach Florida. These experiments provide data for examining the connections with environmental factors (geological/biological patchiness) and for exploring the dependence of clutter on system characteristics such as frequency or bandwidth. A variety of areas with complicated bottom properties are included in the study areas. The diversity of sites allows an excellent opportunity to examine the statistics of scattering from a wide variety of extreme seafloor environments in terms of acoustic clutter. Ground truth consisting of a combination of video and high-resolution side scan and multibeam sonar can be used for estimating heterogeneity of seafloor properties. A digital stereo photogrammetry system will provide estimate roughness properties of seafloor patches. Synthetic aperture sonar data collected from a rippled sandy seabed by APL/UW on their rail facility as part the SAX04 sediment acoustics experiment in fall 2004 will be analyzed to examine the dependence of resolution on the scattering statistics as well as frequency and the propagation environment.

Experimental concepts were developed (in collaboration with Dr. John Osler and Dr. Paul Hines of Defense Research and Development Canada, DRDC) to measure the sound speed dispersion during the SAX04 experiment. The experimental geometry was developed with the goal of being able to make several complementary measurements of sound speed, and an effort is being made to quantify potential sources of uncertainty in each of the measurement approaches. A combination of vector and pressure receivers will deployed during the SAX04 experiment in October, 2004. These will permit measurements of sound speed by: (a) measuring the angle of refraction of energy into the seabed; (b) measuring the time of flight between buried receivers; (c) measuring reflection loss in the water column through a wide range of angles; (d) measuring the impedance of the seabed.

WORK COMPLETED

1) Scattering statistics: As part of 2004 U.S. Office of Naval Research sponsored SAX04, SAS experiments took place about 1 km offshore in water about 17 m (55 ft) deep in the Gulf of Mexico south of Fort Walton Beach, Florida. A bottom mounted rail/mobile tower system was deployed by Applied Physics Laboratory scientists to carry out scattering strength and SAS measurements. The SAS data examined so far were collected over five frequency bands spanning the range from 2 to 100 kHz. Ripples on the sandy bottom can be seen in portions of the image formed from a 60-100 kHz transmitted waveform (Figure 1). Preliminary statistical analysis has been performed on these data showing: 1) SAS data are well approximated with a *K* distribution and 2) agreement with predictions of the relationship between bandwidth and the shape parameter of the *K* distribution based on the model of Abraham and Lyons (2002). Analysis of the SAX04 data has shown that in spite of the fixed resolution cell size yielded by SAS processing, shape parameter estimates were found to increase with range from the sonar. The increase was attributed to multi-path propagation. At increasing distance

from the sonar, scattered returns arising from additional propagation paths arrive in one time window, with the result that two or more resolution cells are contributing, leading to a larger estimate of the shape parameter than would be expected when only the direct path contributes.

2) Sound speed dispersion: As part of the SAX04 experiment, a combination of vector and pressure receivers was employed to make sound speed measurements. These data are currently being analyzed to estimate sound speed dispersion by: (a) measuring the angle of refraction of energy into the seabed using both active sources and ship noise; (b) measuring the time of flight between buried receivers; (c) inversion of ship noise attenuation data via Kramers-Kronig inversion; (d) measuring reflection loss in the water column. Initial results showed significant dispersion in the sandy sediments off Ft. Walton Beach, Florida. A recently discovered complicating factor in using ship noise to estimate dispersion using the vector sensors is the presence of multipath. Estimates of arrival angle using the TV-001 vector sensors give only the *net* acoustic flux so the presence of more that one path biases the result. Full wave simulations carried out by Dave Chapman at DRDC match observed data. The combination of full wave acoustic models of acoustic flux and exact sensor position and orientation should give some indication of the sound speed below 1kHz.

RESULTS

Figure 1 shows an example of the type of SAS images studied. Before evaluating the shape parameter and how it changes with system and geometric parameters, it is necessary to determine how well fit the data are by the K distribution. In order to quantify how much of the data are well fit by the Rayleigh and K distributions, the Kolmogorov-Smirnov (KS) test (Lyons and Abraham, 1999) is applied to normalized SAS data to test the ability of the models to represent the observed data. A mean power level normalizer [e.g., a cell-averaging constant false alarm rate (CFAR) normalizer] is applied to the original complex image data, which results in an image with nearly unit power. The KS test evaluates the maximum difference between the sample cumulative distribution function (CDF) generated by the data and a test CDF which is, in this case, either the Rayleigh or K distribution with their parameters estimated from the data being tested. The Rayleigh distribution only depends on its power, which is estimated by the sample intensity (i.e., the average of the matched filter intensity over the window being tested). As the data have already been normalized to have unit power, this should be near one. Estimation of the K distribution parameters is more involved and employs a method of moments estimator, described in detail in Abraham and Lyons (2002).

For the SAS image data under consideration, windows 1024 samples long (all the along-rail data at a single range) were used to estimate the model parameters and then form the KS test statistic. Using the asymptotic p-value (the probability that a data sample would be rejected when it should be accepted as being well fit by the model under consideration) of the KS test statistic, the data are either accepted as being well fit by the Rayleigh or K distribution or rejected. Figure 2 contains the results for various p-values for the different transmit bands studied. For example, at the $p=0.05$ level, 33% of the 60 – 100 kHz data are well fit by the Rayleigh distribution and 91% are well fit by the K distribution. Based on the acceptance percentages shown in Figure 2, the K distribution is accepted as a good model for these data. It should also be noted that portions of the data collected and analyzed, however, were well fit by the Rayleigh distribution. As the K-distribution has the Rayleigh distribution as a sub-member, the K-distribution will fit these data well too.
The data presented in Figure 3 display a trend toward higher shape parameters (i.e., toward a Rayleigh distribution) with increasing range and with 'spikes' at specific ranges. Preliminary analysis based on

the results of Abraham and Lyons (2004b) indicates that, with respect to array processing, the statistics are most strongly dependent on the beamwidth of the array. Thus, when SAS processing results in constant cross-range resolution with range, the beamforming is not expected to significantly alter the statistics even though many more pings are used at longer ranges. A more likely explanation may be found in accounting for the effects of multipath propagation (Abraham and Lyons, 2004a). An indication of the effect of propagation on the shape parameter is shown as the solid red lines in Figure 3 which correspond to ranges (converted from time using water column sound speed) where multipath start to contribute. The earlier ranges (travel-times) have less or no multipath arrivals while the later ranges (travel-times) do, leading to more scatterers contributing to reverberation and therefore a higher K-distribution shape parameter. A test of this hypothesis involves re-estimating the shape parameter for data that reduces the effect of the multipath. The APL-UW tower contained several receivers of various sizes. Figure 4 shows results of estimates of the shape parameter versus range in the image using receivers of two different sizes. The spike in shape parameter seen at approximately 17 m range is reduced when using data collected with the larger receiver - the smaller beamwidth of the larger receiver reduced excluded the contributing multipath at this range.

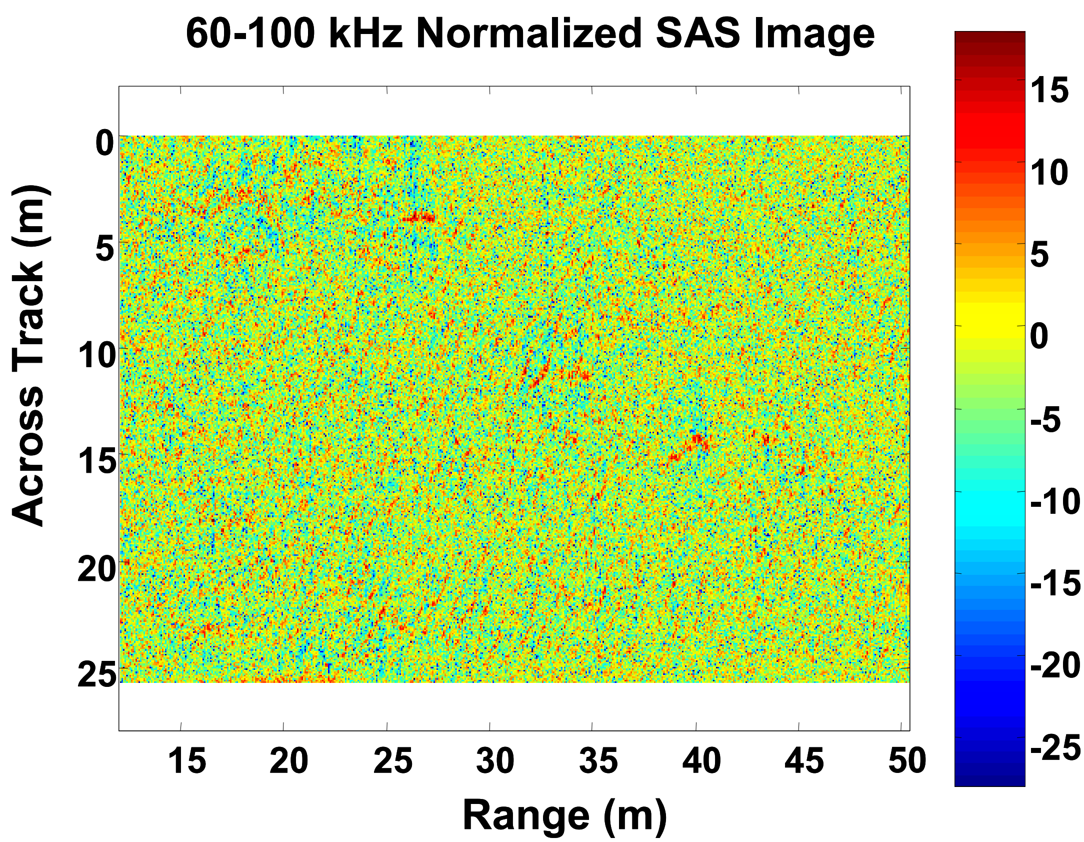

Figure 1. Example of normalized synthetic aperture sonar image. Ripples and possible targets can be seen in this image.

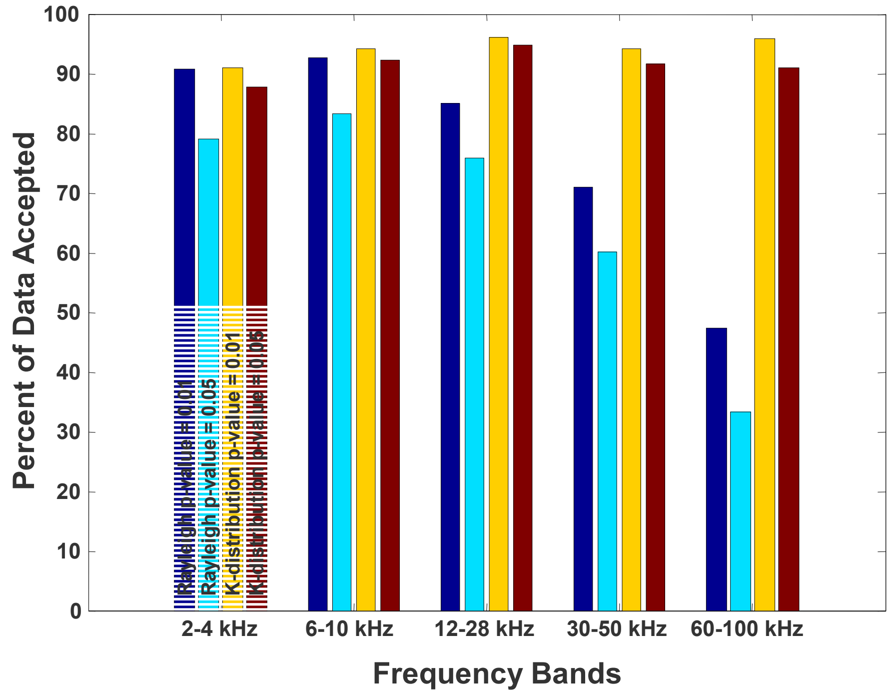

Figure 2. Percent of data accepted as Rayleigh or K distributed based on the Kolmogorov-Smirnov (KS) Test at various levels of false rejection. The p-value is the probability that a data sample would be rejected when it should be accepted as being well fit by the model under consideration

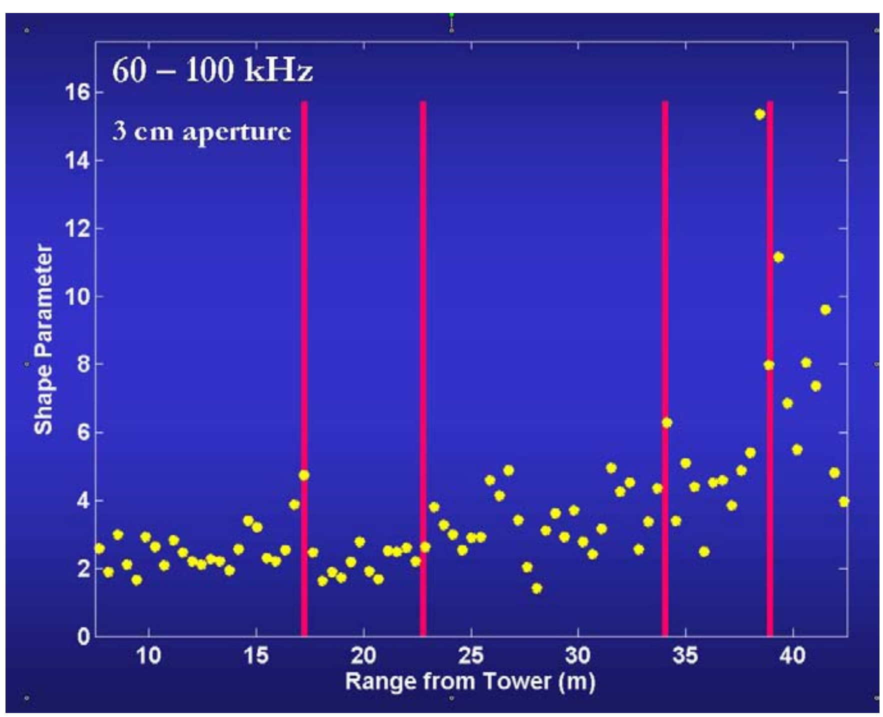

Figure 3. K DistributionShape parameter estimates versus range (symbols) along with lines indicating ranges (converted from travel time) where various multipath contribute (red lines).

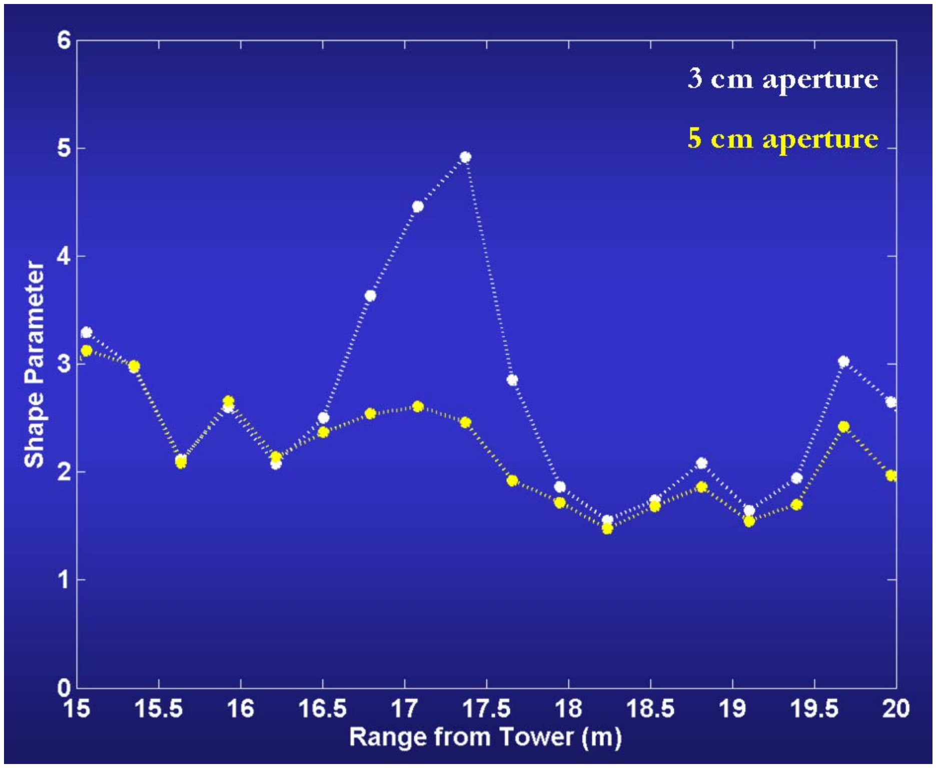

Figure 4. Shape parameter estimates versus range using two different sizes of receiver. The 3cm receiver data is shown in Figure 3.

Figure 5 illustrates the geometry of the ship noise measurements along with the initially assumed refracted arrival paths for ship noise in the sediment by the directional sensors assuming sound speed dispersion. The data set analyzed consists of recordings on three accelerometer channels and the pressure channels housed in the TV-001 vector sensors buried in approximately 0.5 and 1 m of sediment and a nearby sensor lying on the sediment interface. The pressure and acceleration data were filtered into 1024 sub-bands using a discrete Fourier transform (DFT). Using the time series of the pressure and the acceleration components, the arrival angle of acoustic energy as a function of frequency can easily be determined from the magnitudes of the y- and z-components of the intensity spectrum (Lyons, et al., 2005). Figure 6 displays the measured incident grazing angle at the sensor buried at .894 m depth as a function of frequency along with the full wave modeling results of Dave Chapman. The oscillatory nature of the arrival angle are evident and are due to interference between the paths shown in Figure 5 and additional energy arriving through the sediment (direct and evanescent). This interference complicates the original simple plane wave Snell's Law assumption, but it is hoped that the combination of exact sensor positions and full wave modeling will yield some estimate of the sound speed below 1 kHz.

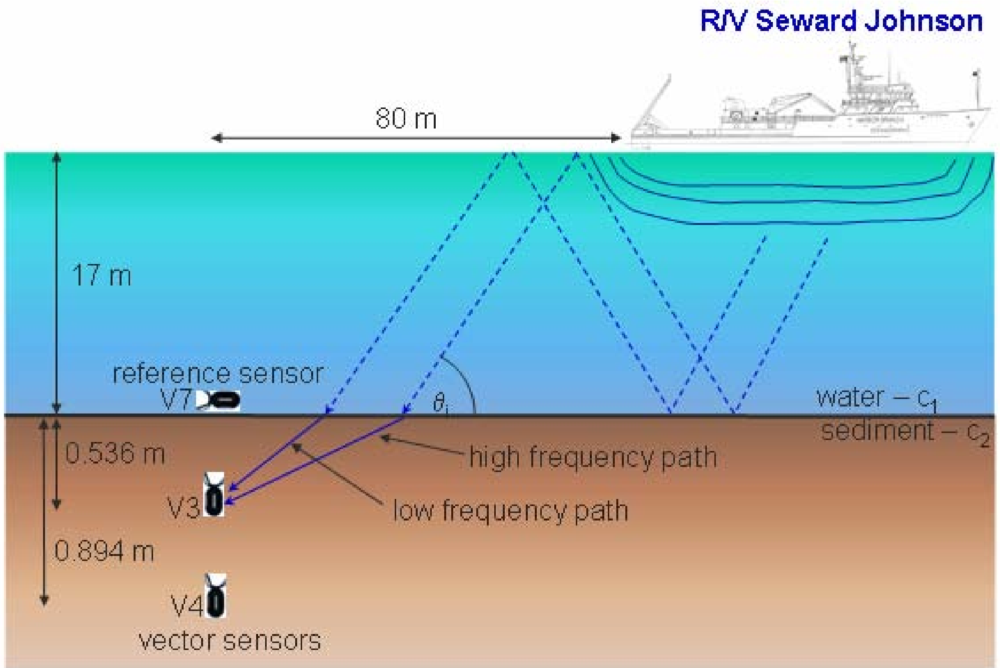

Figure 5. Geometry of vector sensor field with respect to the moored RV Seward Johnson showing dominant arrival path of ship noise at the vector sensor array.

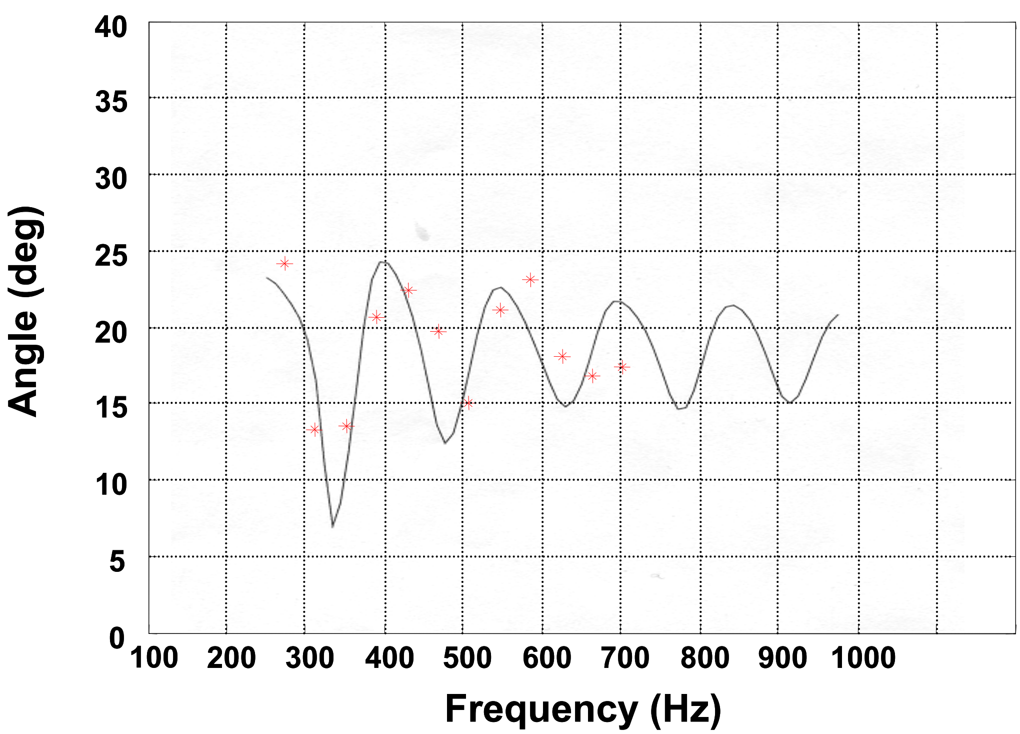

Figure 6. Measurements of arrival angle from ship noise data (symbols) compared with full wave modeling results (black line). The oscillatory behavior is due to interference of two multipaths at the buried vector sensor.

IMPACT/APPLICATIONS

The scattering statistics research is providing an improved understanding of the link between environmental parameters and system factors in causing clutter, as well as models and methods for characterizing, predicting and mitigating clutter. This study is leading to methods for modeling and predicting acoustic clutter that may be used to minimize the negative impact of clutter on detection and classification of targets on or near the seafloor in shallow water. Knowledge gained will help in the development of reverberation simulation tools, adaptive systems for sonar clutter reduction and rapid environmental assessment techniques for estimating the strength of clutter for a given area.

The study of the frequency dependence of sediment sound speed has implications for the operation of sonar systems and methods used by the Navy. This study will lead to a greater understanding of dispersion in marine sediments and improved methods for modeling dispersion. Immediate potential impacts could be increasing coverage rates of mine hunting sonar by optimizing the frequencies used. Prediction of the coverage rates of mine hunting sonar could also be improved with knowledge of the seafloor environment.

TRANSITIONS

The statistical models of clutter that have been explored and developed are being quickly incorporated into the ARL-PSU Technology Requirements Model (TRM), a high fidelity, physics-based digital simulator. Discussions are also under way to include models into simulations of Synthetic Aperture Sonar being developed by APL-UW. These models will allow efficient simulation of false alarms and false targets for many different scenarios for which experimental data do not exist.

RELATED PROJECTS

A related ONR project (Grant N00014-06-1-0245) is Characterizing and Modeling the Torpedo Clutter Environment managed by David Drumheller, code 333. Items were purchased for this project under a DURIP (Grant N00014-04-1-0445).

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